

methods and apparatus for preparing the single and double heterostructures are disclosed, for example, in U.S. Pat. No. 5,554,220, which is herein incorporated in its entirety by reference. The subject invention as disclosed herein may be used in conjunction with co-pending applications, "High Reliability, High Efficiency, Integratable Organic Light Emitting Devices and Methods of Producing Same;" "Novel Materials for Multicolor LED's;" "Electron Transporting and Light Emitting Layers Based on Organic Free Radicals;" "Multicolor Display Devices;" "Red-Emitting Organic Light Emitting Devices (LED's);" and "High Efficiency Organic Light Emitting Device Structures;" each of said co-pending application being filed on Dec. 23, 1996, and being herein incorporated in their entirety by reference. The subject invention may also be used in conjunction with co-pending U.S. Ser. Nos. 08/354,674; 08/613,207; 08/632,316; 08/632,322; and 08/693,359; which are also herein incorporated in their entirety by reference.

[0016] The single or double heterostructures, as referred to herein, are intended solely as examples showing how-an OLED embodying the subject invention may be fabricated without in any way intending the invention to be limited to the particular sequence or order of making the layers shown. For example, a single heterostructural OLED of the subject invention includes a flexible substrate, which is preferably transparent; a first electrode, which may typically be an indium tin oxide (ITO) anode layer; a hole transporting layer; an electron transporting layer; a second electrode layer, for example, a metal cathode layer of Mg:Ag; and a metal protective layer, for example, made of a layer of Ag, for protecting the Mg:Ag cathode layer from atmospheric oxidation. A double heterostructure would also include an additional layer containing an emissive material. This additional layer is herein referred to as a "separate emissive layer" so as to distinguish it from the other layers, since the hole transporting layer and the electron transporting layer can be made to produce electroluminescent emission without the need for this separate emissive layer.

[0017] Although not limited to the thickness ranges recited herein, the ITO anode layer may be about 1000 Å ($1 \text{ Å} = 10^{-8} \text{ cm}$) to greater than about 4000 Å thick; the hole transporting layer about 50 Å to greater than about 1000 Å thick; the layer containing emissive material about 50 Å to about 200 Å thick; the electron transporting layer about 50 Å to about 1000 Å thick; and each metal layer, about 50 Å to greater than about 100 Å thick, or substantially thicker if the cathode layer is not intended to be transparent.

[0018] The ability to achieve highly flexible displays vacuum-deposited molecular organic materials, which have stable electroluminescent properties, depends on, inter alia, the following two factors. First, the molecular bonds responsible for the mechanical properties of the thin films comprising the OLED needs to be reasonably tolerant of the stress applied to the structure on bending, and, second, the substrates needs to be sufficiently flat and uniform such that mechanical defects are not formed during growth or flexing.

[0019] Concerning the first factor, virtually all organic materials used in vacuum-deposited OLED's are held together by highly flexible van der Waals bonds. Previously, it has been shown, Y. Zhang and S. R. Forrest, Phys. Rev. Lett. 71, 2765 (1993), that the bonding of aromatic molecules similar to those used in OLED's is highly compress-

ible. For example, it was shown that the compressibility of the van der Waals-bonded naphthalene-based molecular crystal NTCDA has a roughly 20-times-higher compressibility than most ductile metals such as In or Al. C. Kittel, Solid State Physics, 4th ed. (Wiley, New York, 1971) p. 143. While not intending to be limited to the theory of why the subject invention is capable of producing stable electroluminescence, such considerations help to explain why the molecular materials disclosed herein are sufficiently ductile to undergo significant stress without cracking.

[0020] The second factor, that the substrates used be sufficiently flat, was established through the use of images produced by an atomic force microscope. These images, such as shown in FIG. 4, shows that the ITO surface had a rms roughness of only 1.8 nm, whereas the polyester surface of the flexible was somewhat rougher, with a rms value of 2.8 nm. Although there was some variation from substrate to substrate, ITO surface roughness did not exceed 3.6 nm. In either case, the substrates were sufficiently smooth (i.e., the height of the surface features was a small fraction of the total device thickness) such that no significant damage was observed for the subject OLED heterostructure on growth or bending.

[0021] Based on such considerations, the subject devices grown on flexible substrates were found to have efficiencies comparable with conventional vacuum-deposited OLED's grown on glass and, furthermore, such devices were found to be mechanically robust.

[0022] This invention will now be described in detail with respect to showing how certain specific representative embodiments thereof will be made, the materials, apparatus and process steps being understood as examples that are intended to be illustrative only. In particular, the invention is not intended to be limited to the methods, materials, conditions, process parameters, apparatus and the like specifically recited herein.

EXAMPLES

[0023] In the cross section of the particular embodiment of the invention illustrated in FIG. 1, a flexible substrate 2 for the device is comprised of any suitable flexible polymer sheet such as a polyester. Preferably, the flexible substrate is capable of being bent to a radius of curvature down to 0.5 cm or less. The flexible substrate 2 is precoated with a thin film 4 of indium tin oxide, ITO, such as is available from Southwall Technologies, Inc., 1029 Corporation Way, Palo Alto, Calif., 94303, Part No. 903-6011. In this particular embodiment, the hole transport layer 6 was comprised of N,N'-diphenyl-N,N'-bis(3-methylphenyl)-1-1'-biphenyl-4,4'-diamine (TPD), and the electron transporting layer 8 was comprised of tris-(8-hydroxyquinoline) aluminum (Alq_3). Other non-polymeric materials, such as known in the art for preparing hole transporting layers, electron transporting layers and emissive layers may also be used. The hole conducting layer 6 of TPD is formed on top of the hole injecting ITO layer 4, and a light emitting layer 8 of Alq_3 is formed on the layer 6. Alternatively, a single layer can be used in place of the layers 6 and 8 in which TPD and Alq_3 are combined. A layer 10 of Mg-Ag is formed on the Alq_3 layer 8, and a layer 12 of Ag is formed on the Mg-Ag layer 10. A power supply 14 is connected between the Ag layer 12 and the precoated ITO layer 4.